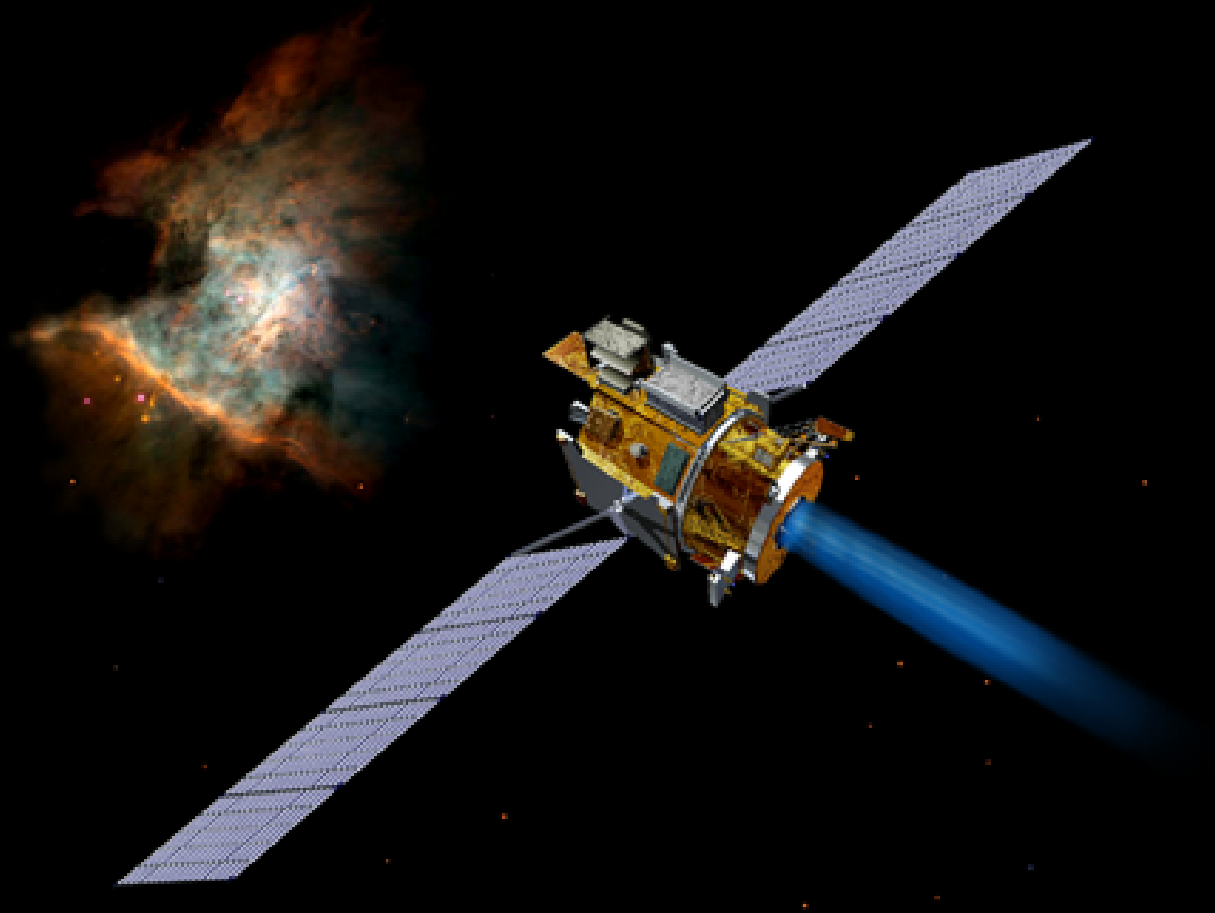


Deep Space 1 Autonomous Navigation



Ed Riedel, Shyam Bhaskaran, Don Han, Brian Kennedy, Steve Synnott, Mike Wang, Robert Werner
Jet Propulsion Laboratory
California Institute of Technology

Deep Space 1 Project

- Primary objective
 - Flight validate advanced technologies selected by the New Millennium program
- Launched on October 24, 1998
 - 39 months from concept initiation
 - 26 months from formulation of level-1 requirements.
- Primary mission ended on September 18, 1999
- Extended mission devoted to encounters in 2001 with Comet Wilson-Harrington and Comet Borrelly



Boeing Delta 7326 launch vehicle
lifts off with *DS1* onboard

Primary Mission Trajectory Plan

**Asteroid
1992 KD**

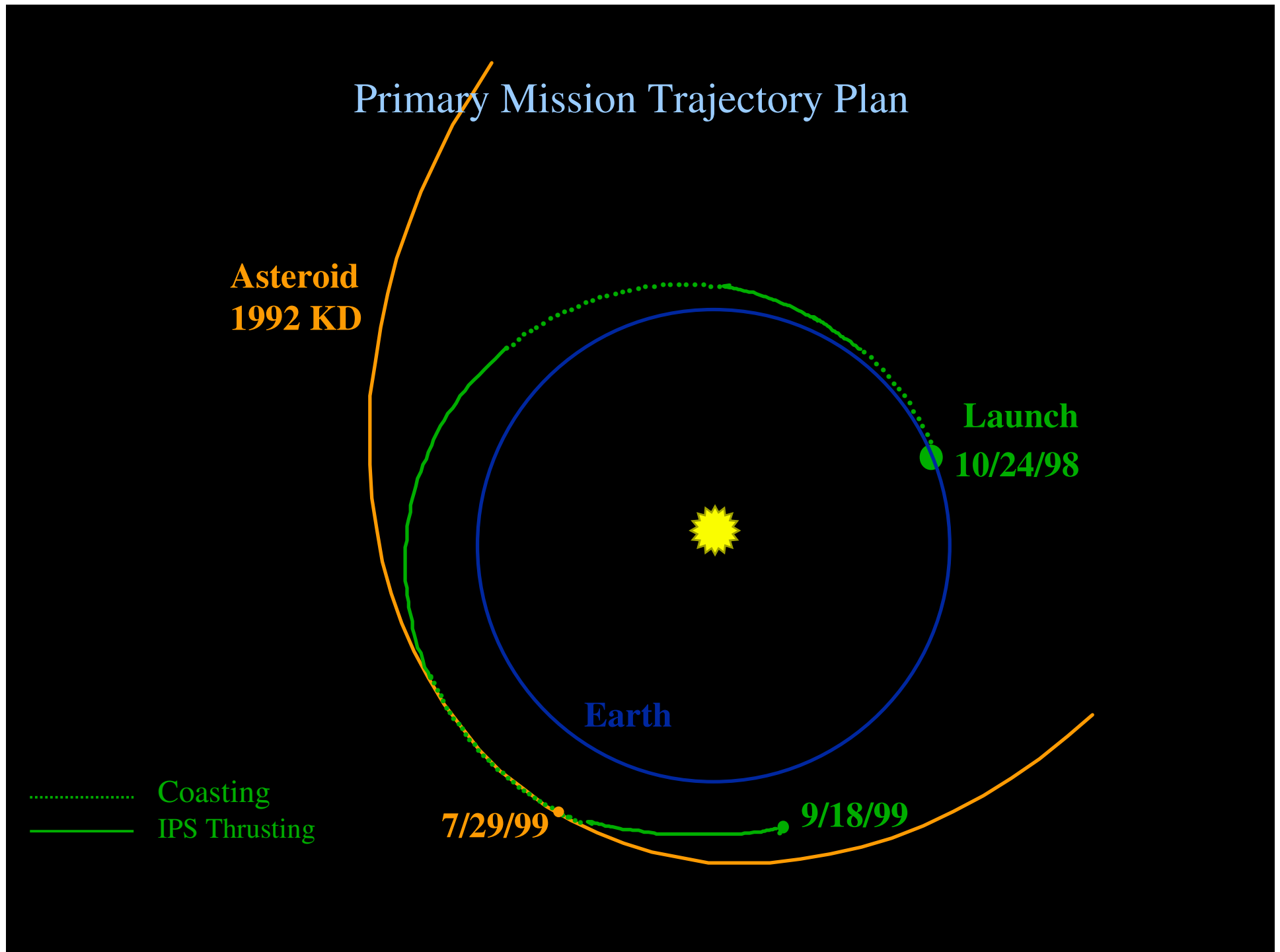
**Launch
10/24/98**

Earth

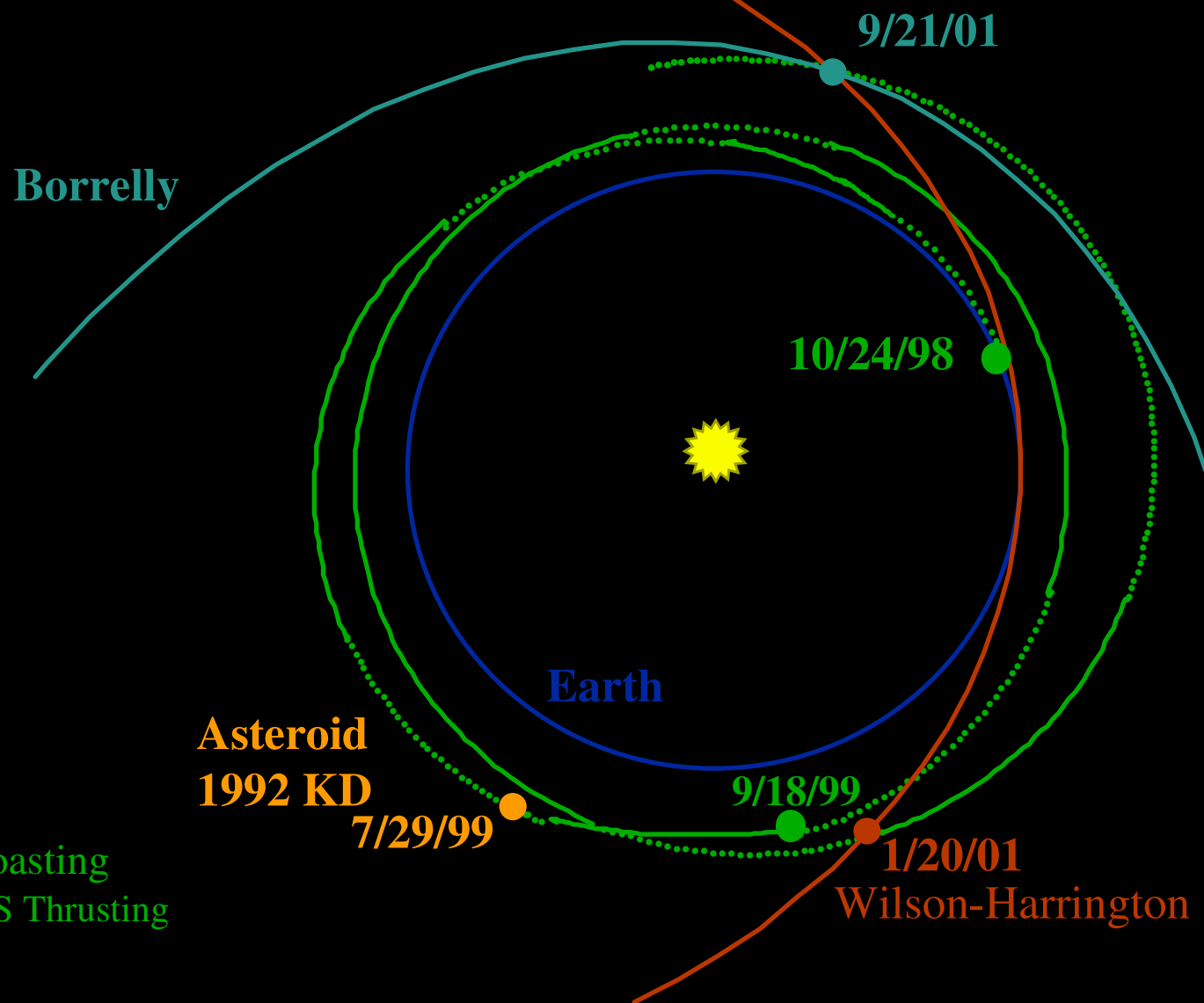
..... Coasting
—— IPS Thrusting

7/29/99

9/18/99

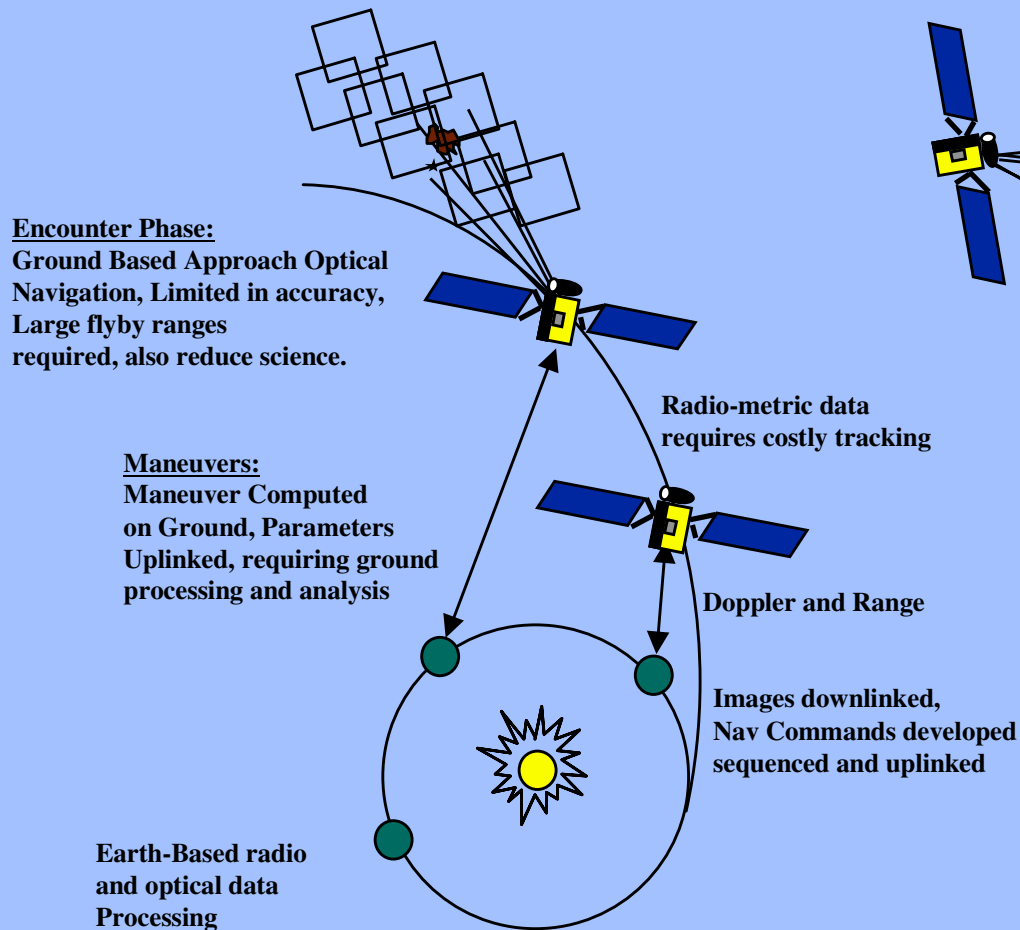


Extended Mission Trajectory Plan

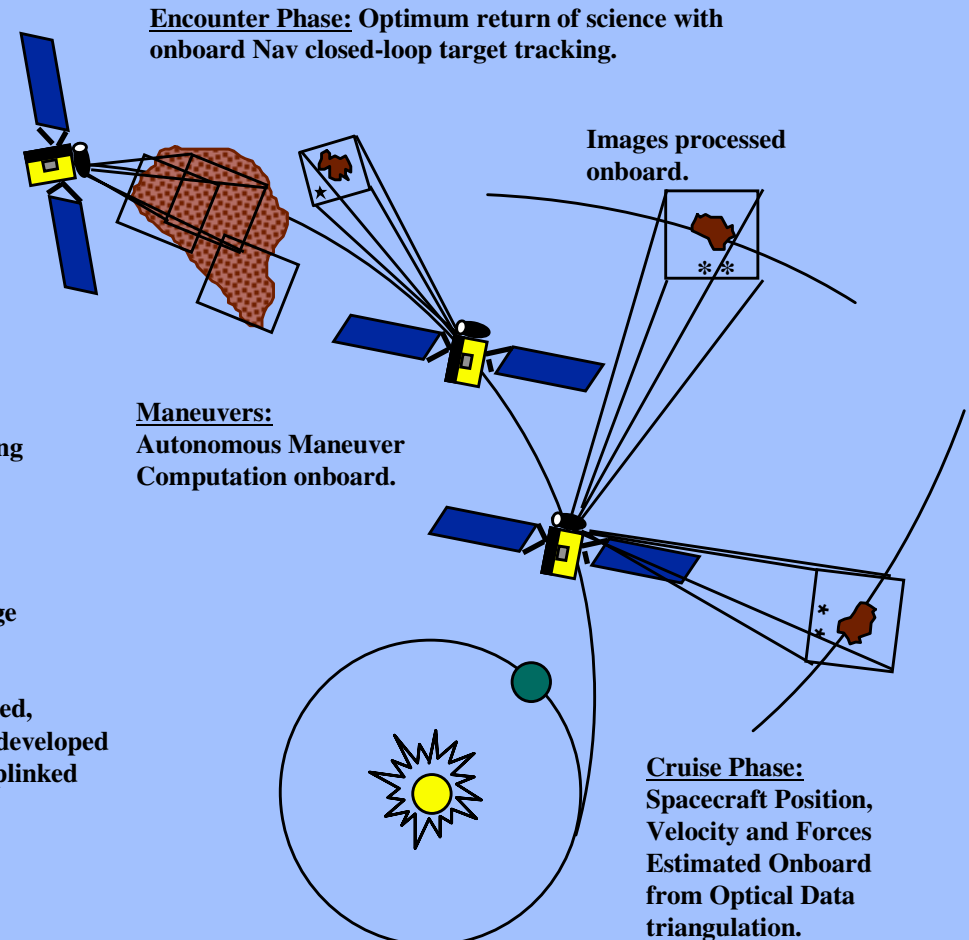


AUTONOMOUS OPTICAL NAVIGATION (AutoNav) for NEW MILLENNIUM *DS1*

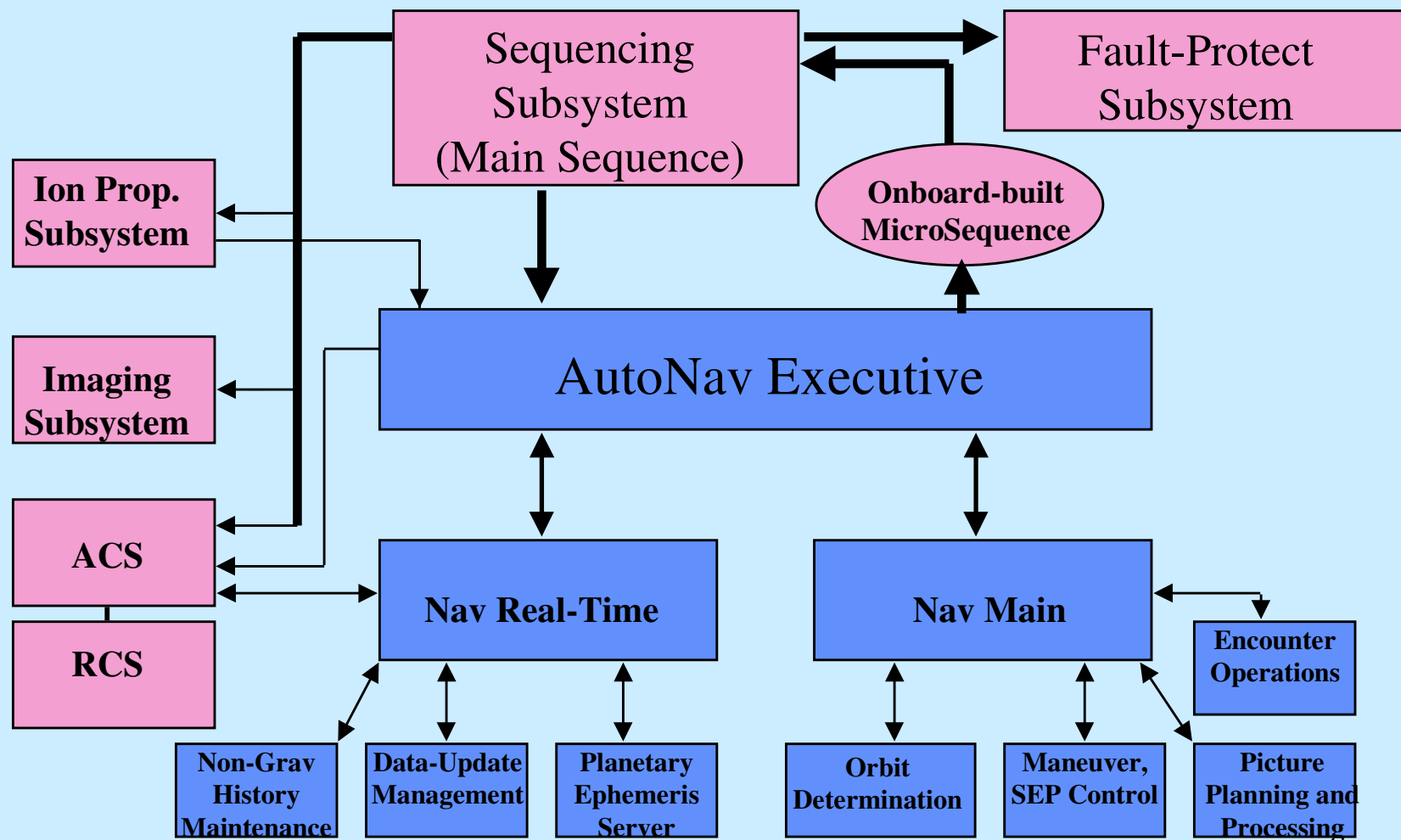
CONVENTIONAL NAVIGATION



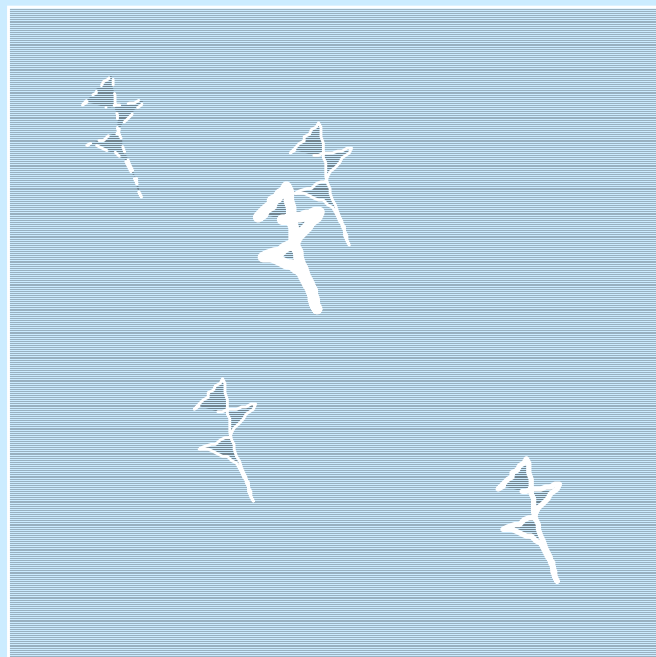
AUTONOMOUS NAVIGATION



DS1 AutoNav System

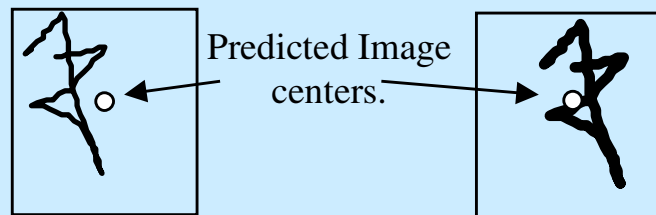


High-precision Astrometry for Navigation in Space from a Deadband-motioned Camera, using Multiple Cross-Correlation.

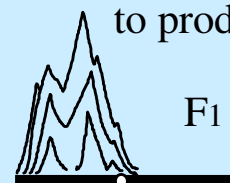


Long Duration Exposure of Asteroid and Background Stars

Extracted Data Blocks

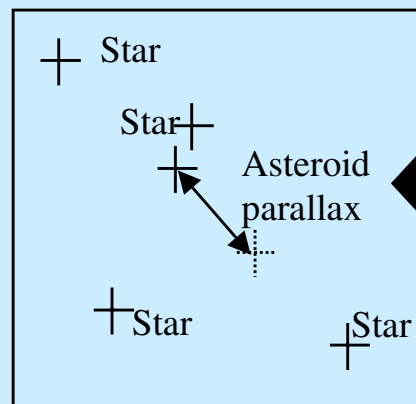
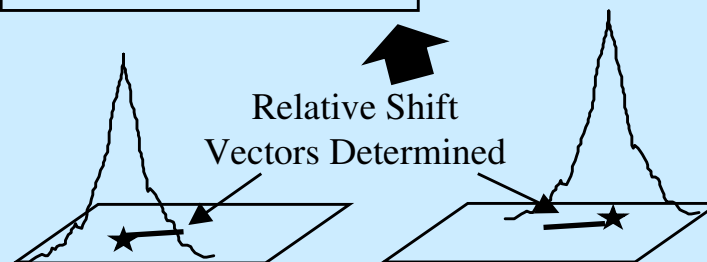


Normalization of Data Blocks
to produce Image Filters



Convolutional Inner Product Responses:

$$F_1 \otimes F_2 \text{ vs. } F_2 \otimes F_1$$



Ensemble of Star and Asteroid Shift Vectors Determine to High Precision Locations of all Images in Picture, from which Precise Navigation Data (measurement of parallax) is Obtained.

Orbit Determination

- **Dynamical equations of motion**
 - Includes central body acceleration, 3rd body perturbations from other planets, solar radiation pressure, thrust from the ion engines, and miscellaneous accelerations
 - 2nd order differential equation modeled as two 1st order differential equations

$$\dot{\mathbf{r}} = \mathbf{v}$$

$$\dot{\mathbf{v}} = -\frac{\mu_s}{r^3}\mathbf{r} + \sum_{i=1}^{n_p} \mu_i \left[\frac{\mathbf{r}_{ri}}{r_{ri}^3} - \frac{\mathbf{r}_{pi}}{r_{pi}^3} \right] + \frac{AG}{mr^3}\mathbf{r} + \frac{k}{m}\mathbf{T} + \mathbf{a}$$

where

\mathbf{r} = the heliocentric cartesian position vector of the spacecraft

\mathbf{v} = the heliocentric cartesian velocity vector of the spacecraft

\mathbf{r}_{pi} = the heliocentric cartesian position vector of the i th perturbing planetary body

\mathbf{r}_{ri} = the position of the spacecraft relative to the i th perturbing body

μ_s = the gravitational constant of the sun

μ_i = the gravitational constant of the i_{th} perturbing planet

n_p = the number of perturbing planets

A = the cross -sectional area of the spacecraft

G = the solar flux constant

\mathbf{T} = the thrust vector from the ion engine

k = the thrust scale factor

m = the spacecraft mass

\mathbf{a} = miscellaneous accelerations acting on the spacecraft

Orbit Determination - Filter

Given \mathbf{q}^* , the nominal trajectory parameters, as

$$\mathbf{q}^* = [\mathbf{r} \quad \mathbf{v} \quad k \quad \mathbf{a}]$$

Filter estimates corrections, \mathbf{q} , to nominal trajectory parameters

$$\mathbf{q}(t) = [\Delta x \quad \Delta y \quad \Delta z \quad \Delta \dot{x} \quad \Delta \dot{y} \quad \Delta \dot{z} \quad \Delta k \quad \Delta a_x \quad \Delta a_y \quad \Delta a_z]$$

The correction at time t is a linear mapping of the correction from time t_0

$$\mathbf{q}(t) = \Phi \mathbf{q}(t_0)$$

where Φ , the state transition matrix, is defined as

$$\Phi(t) = \frac{\partial \mathbf{q}^*(t)}{\partial \mathbf{q}^*(t_0)}$$

Orbit Determination - Filter

(continued)

The partial derivatives of the observed pixel and line locations, p , l , with respect to the state, at time t is

$$\mathbf{H}(t) = \begin{bmatrix} \partial p / \partial \mathbf{r} & 0_{1 \times 7} \\ \partial l / \partial \mathbf{r} & 0_{1 \times 7} \end{bmatrix}$$

This can be mapped back to the epoch, t_0 , via the state transition matrix

$$\tilde{\mathbf{H}}(t_0) = \mathbf{H}(t)\Phi$$

The minimum variance least squares solution to the epoch state corrections is

$$\hat{\mathbf{q}} = \left[\mathbf{P}_0 + \tilde{\mathbf{H}}^T \mathbf{W} \tilde{\mathbf{H}} \right]^{-1} \tilde{\mathbf{H}}^T \mathbf{W} \mathbf{Y}$$

where

\mathbf{P}_0 = the a - priori covariance of the state parameters

\mathbf{W} = the weighting values of the pixel and line observables

\mathbf{Y} = the residual vector between the observed pixel/line locations and their predicted values

Adjusting a Low-Thrust Trajectory (And Targeting for Encounter)

X_e = Target encounter conditions ($B \cdot R, B \cdot T, tof$)

ΔX_e = Deviations from desired encounter

α_i = Rt. ascension of thrust segment i

δ_i = Declination of thrust segment i

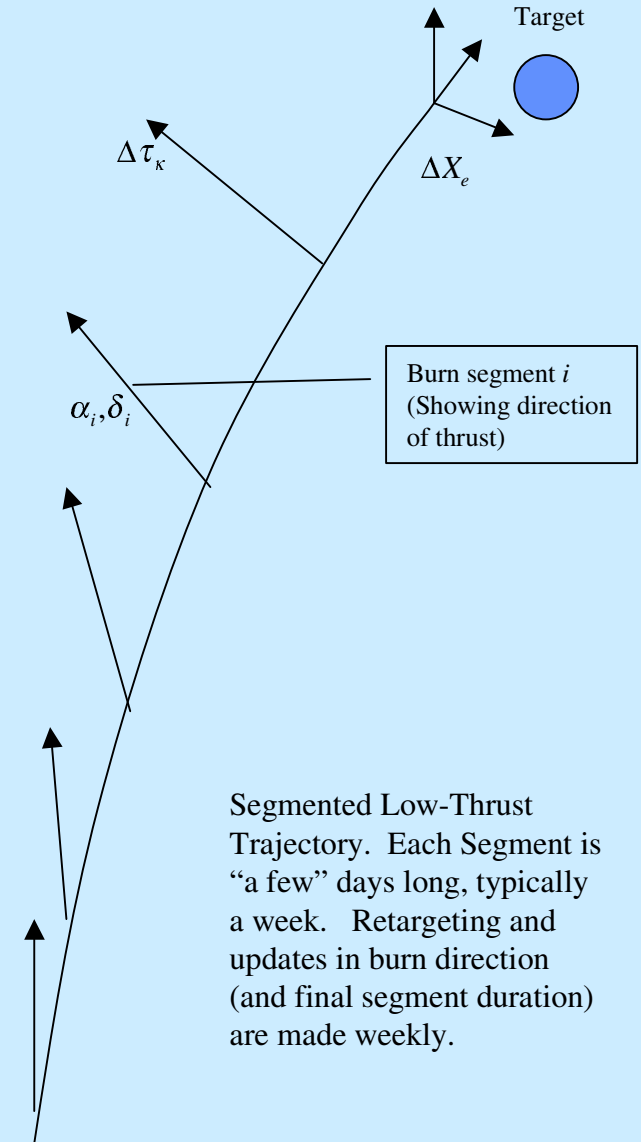
τ_κ = Burn duration of final segment κ

$\Delta X_e = K \Delta s$, where. ..

$$K^T = \begin{bmatrix} (\partial X_e / \partial \alpha_{k_1}) \\ (\partial X_e / \partial \delta_{k_1}) \\ (\partial X_e / \partial \alpha_{k_1+1}) \\ (\partial X_e / \partial \delta_{k_1+1}) \\ \vdots \\ (\partial X_e / \partial \alpha_{k_2}) \\ (\partial X_e / \partial \delta_{k_2}) \\ (\partial X_e / \partial \tau_\kappa) \end{bmatrix}, \text{ and... } \Delta s = \begin{bmatrix} \Delta \alpha_{k_1} \\ \Delta \delta_{k_1} \\ \Delta \alpha_{k_1+1} \\ \Delta \delta_{k_1+1} \\ \vdots \\ \Delta \alpha_{k_2} \\ \Delta \delta_{k_2} \\ \Delta \tau_\kappa \end{bmatrix}$$

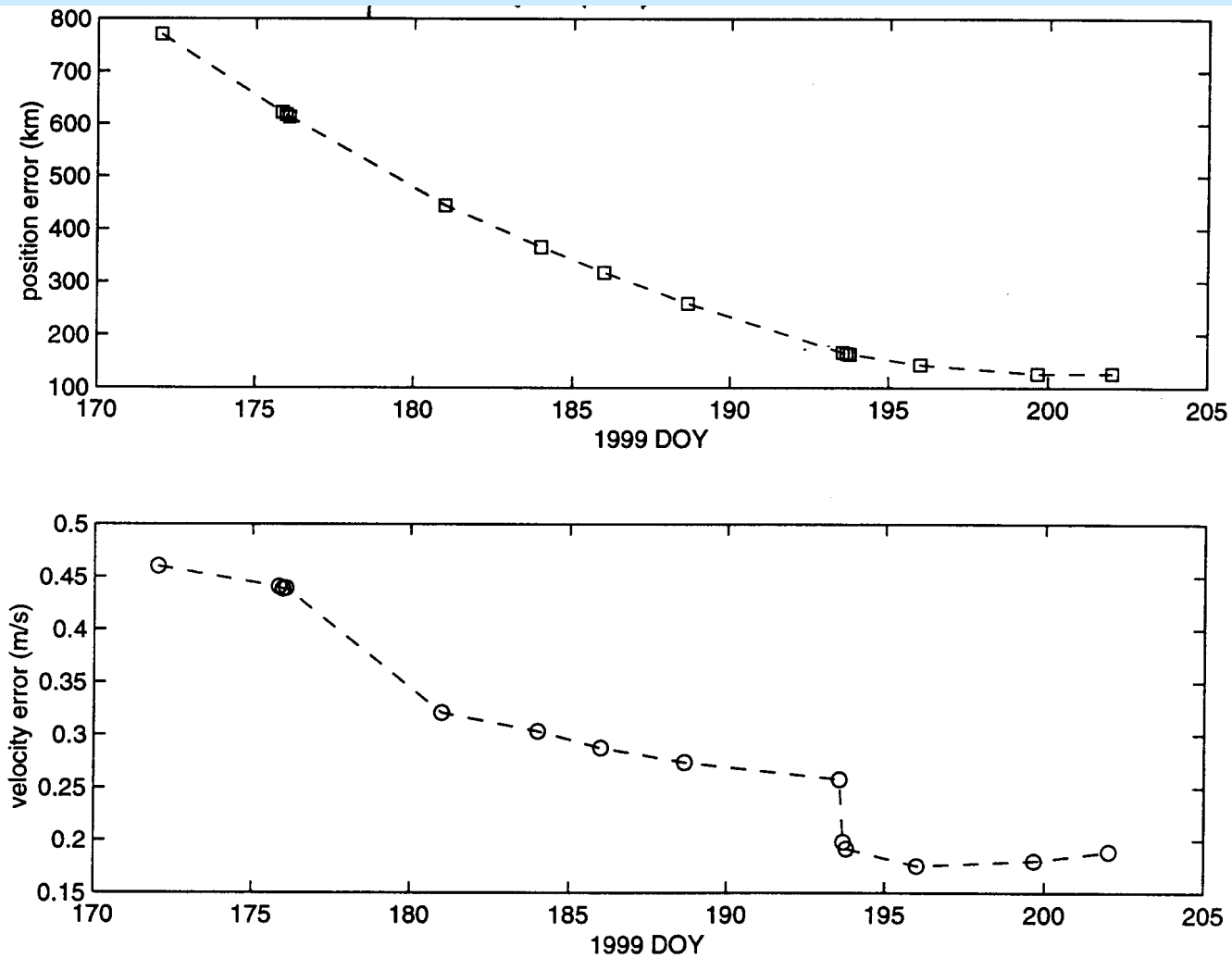
Then, by the calculus of variations,

$$\Delta s = K^T (K K^T)^{-1} \Delta X_e$$

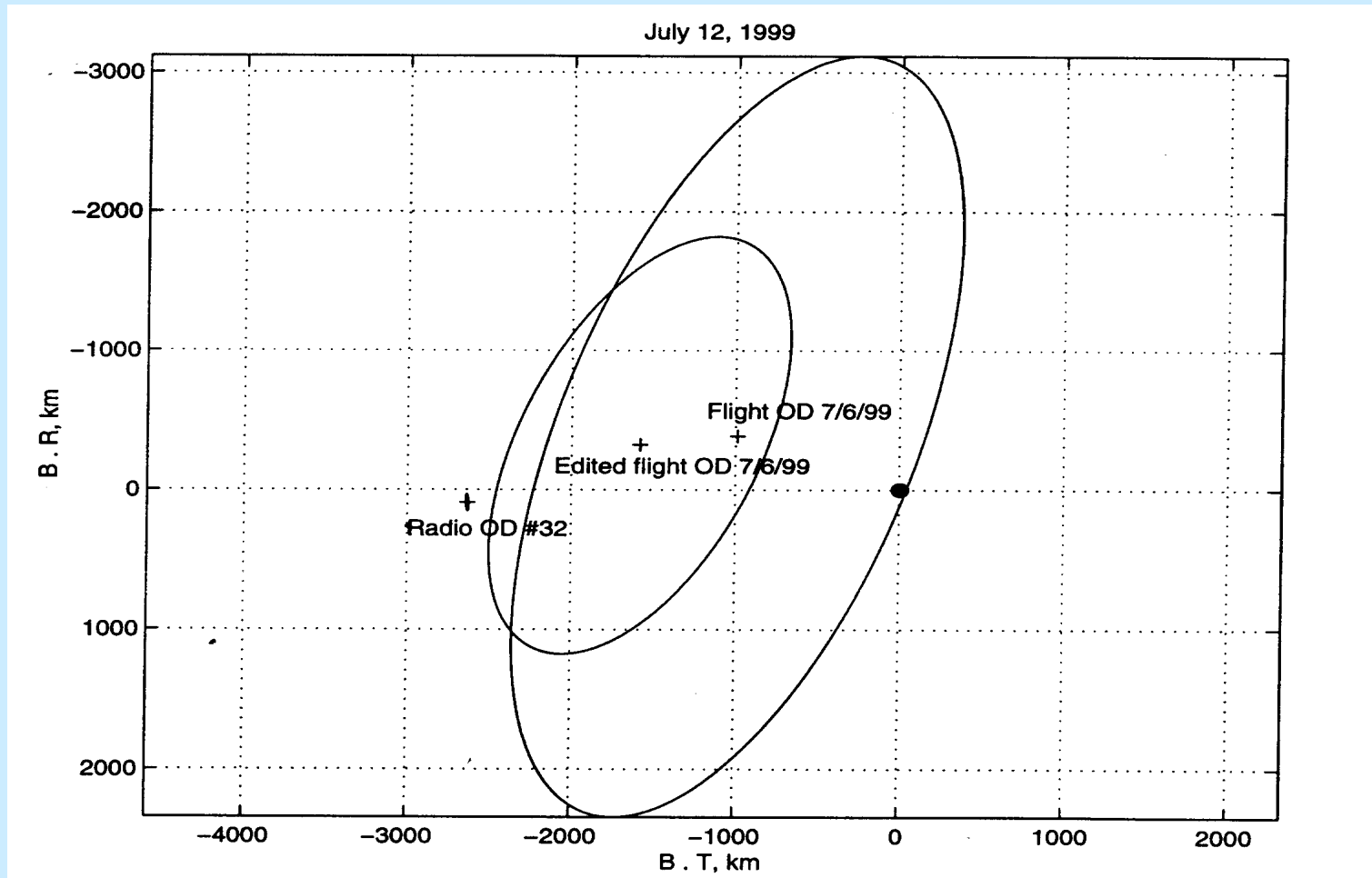


Performance of AutoNav on Approach to Braille

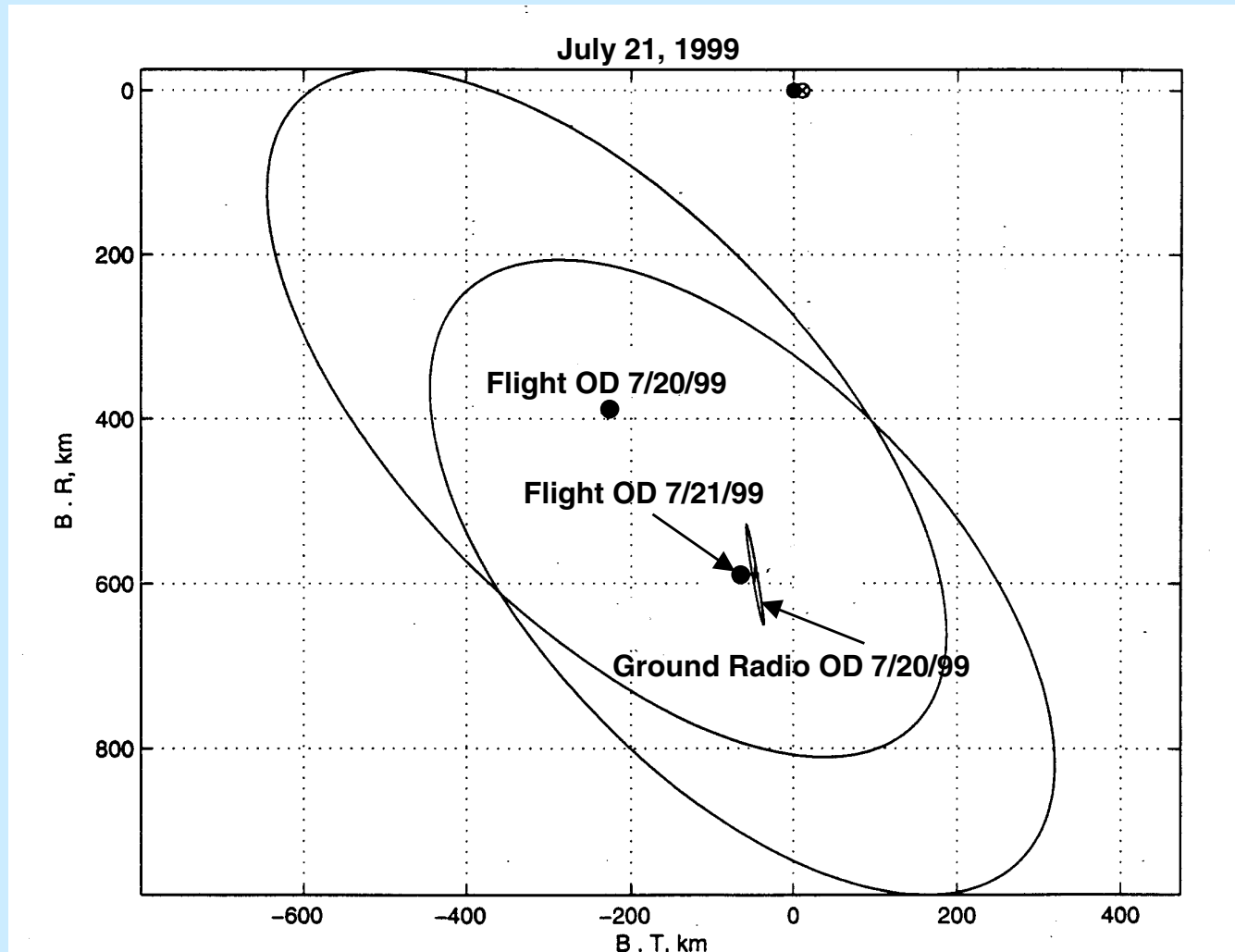
Flight OD vs. Ground Radio OD 7/21/99



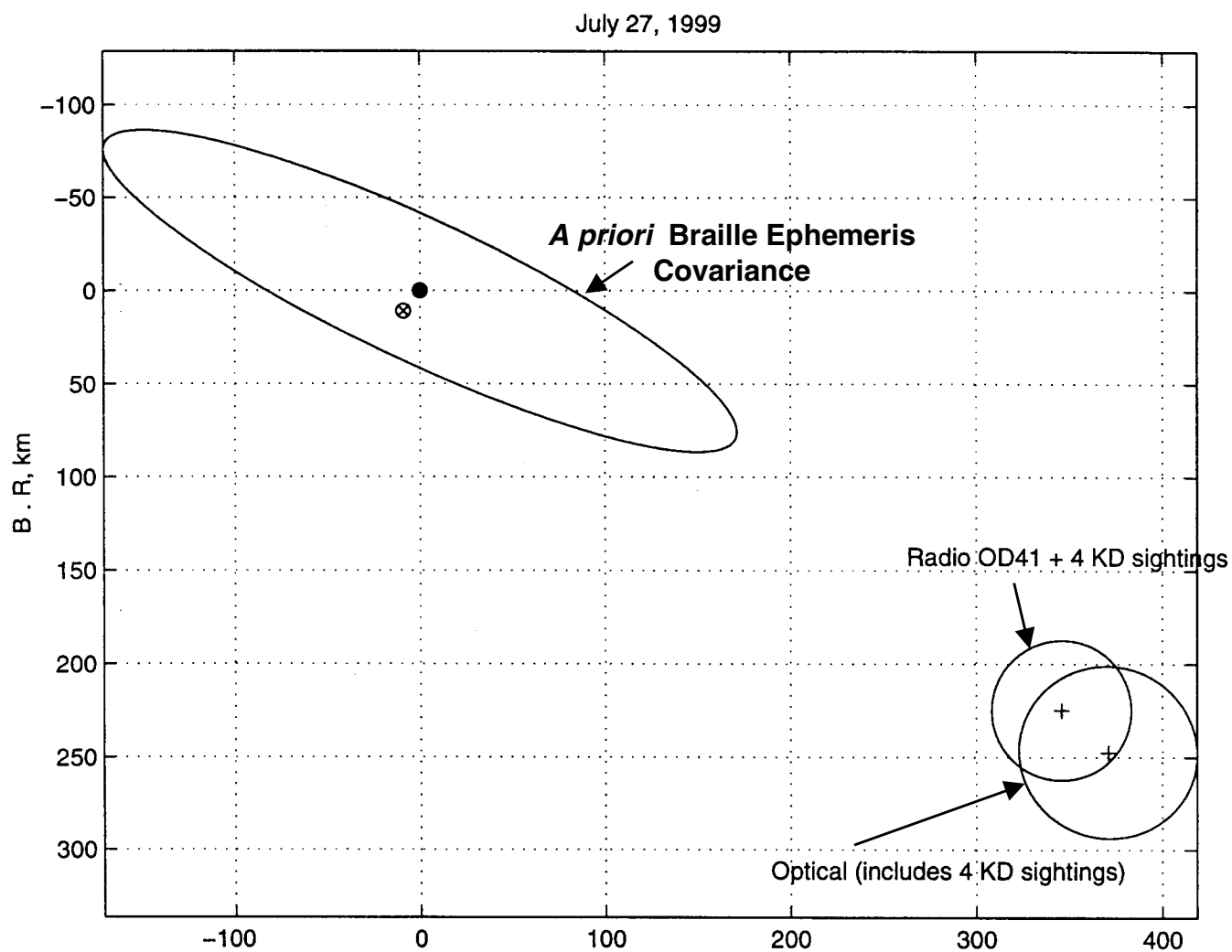
Performance of AutoNav on Approach to Braille



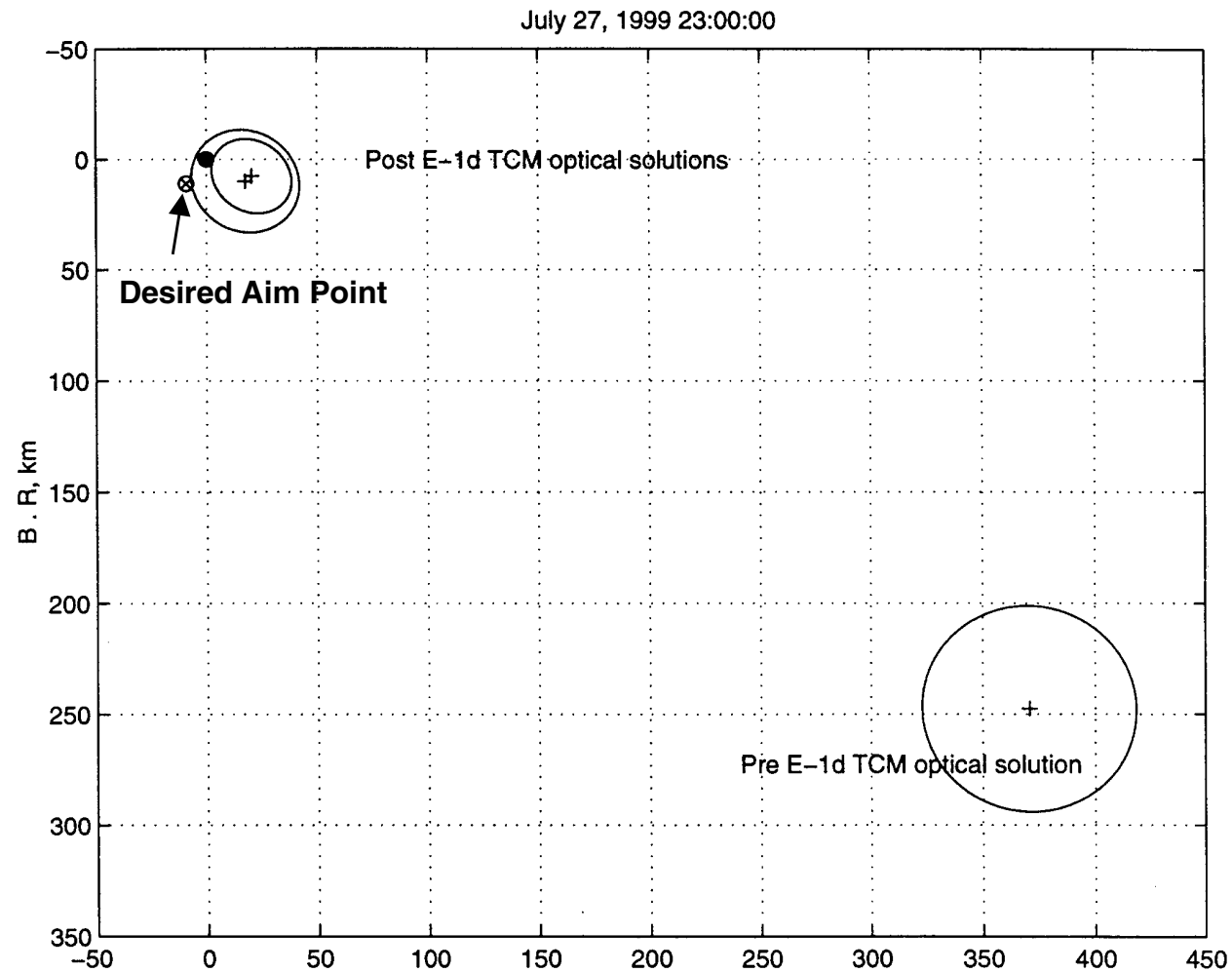
Performance of AutoNav on Approach to Braille



Performance of AutoNav on Approach to Braille



Performance of AutoNav on Approach to Braille



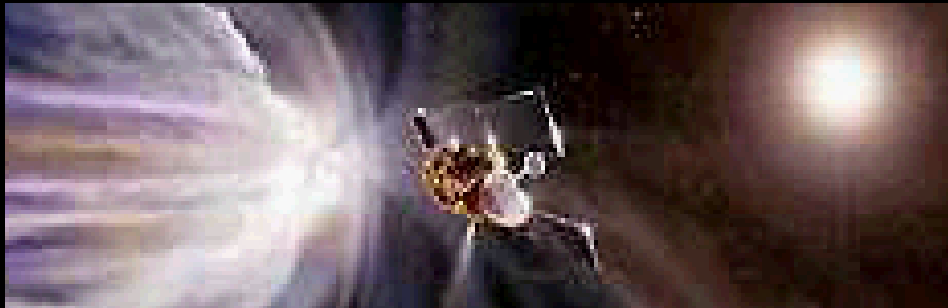
Countdown of Encounter Events

- **-5 Day TCM:** planned optical only (using onboard-planned, taken images of non-Braille beacons, edited on ground, shipped to s/c).
- **-3.0 day PhotoOp:** Braille “phantom” detected, but with insufficient confidence (and “close-enough” to nominal position) to cancel -2 Day TCM.
- **-1.5 day PhotoOp:** 2 “reliable” but very-dim images, for -1.2 Day TCM design (AutoNav not yet locked on).
- **-1 day PhotoOp:** “reliable” but still very-dim images from -24hr PhotoOp indicate no 18 hour TCM necessary.
- **-17hr PhotoOp,** strong signal, AutoNav “locks-on” to Braille. S/C safes at end of Photo-Op Session, due to code-bug in Nav.
- **-12 hr TCM** cancelled due to safing recovery.
- **-6hr TCM:** Existing optical data collected and “seeded onboard” with optical-only design (using latest available -17hr data). -3hr TCM cancelled.
- **-6hr TCM:** executes nominally
- **Down to ACA-70 minutes:** AutoNav takes and processes data normally keeping Braille in FOV. No Science frames taken or preserved.

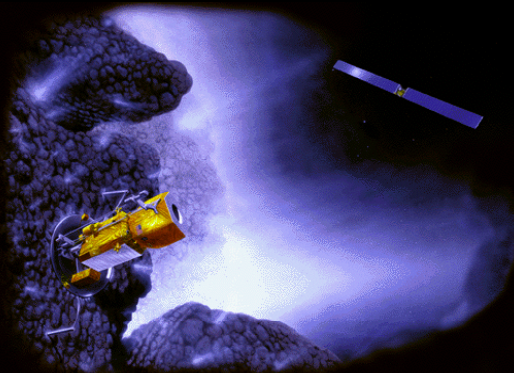
Countdown of Encounter Events (Continued)

- **ACA-27 minutes**, switch to APS sensor. No signal from Braille comes above AutoNav APS threshold.
- **ACA-20 minutes**, unknown signal (cosmic ray?) spoofs AutoNav into 1/4 APS FOV correction. Braille still in FOV of APS, CCD, no Science frames taken.
- **Down to ACA-3 minutes:** Braille in APS and CCD FOV, no Science frames taken or preserved.
- **ACA-150 seconds**, first CCD Science frame taken. Braille barely out of MICAS CCD FOV due to picture-editing, out of all subsequent picture FOV's.
- **ACA-20 seconds**, s/c stops tracking Braille inbound.
- **Inside 20 seconds**, Braille in the IR FOV.
- **ACA+15 minutes**, s/c back on nominal Braille track. First returned close images of Braille. APS images indicate extraordinarily dim image (10 DN, expected 1000 DN). CCD images 400DN, 1/10 "fullwell", expected 1/2 to 1 "fullwell".) -- and this was the "bright side."
- **Post Encounter reconstruction:** indicates approach Braille images 1 to 2 Magnitudes dimmer than outbound, perhaps due to presented geometry of irregular figure. Outbound images also very dim.

Missions and Mission-Types that can (or are planning to) use *DS1* AutoNav to Advantage

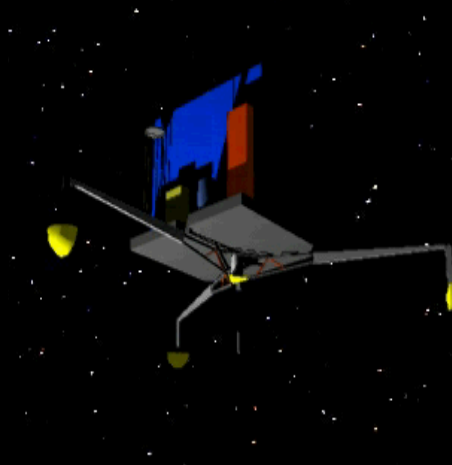
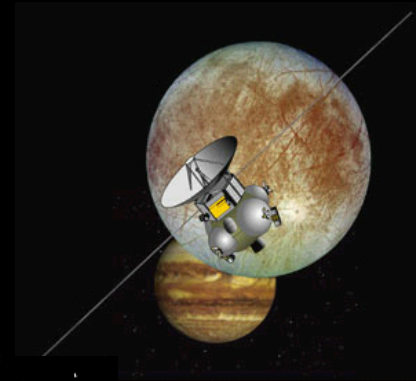


Stardust: Missions requiring precise terminal targeting of spacecraft position and/or remote sensing instruments..



ST4: Missions requiring autonomous precision landing and/or minimum tracking.

Europa Orbiter: Missions with very sensitive trajectory control requirements and/or extreme fuel constraints.



Deep Impact: Missions with autonomously delivered and/or guided penetrators.